

Completely Independent Spanning Trees in Some Regular Networks

Benoit Darties¹, Nicolas Gastineau^{*1,2} and Olivier Togni¹

¹*LE2I, UMR CNRS 6306 , Université de Bourgogne, 21078 Dijon
cedex, France*

²*LIRIS, UMR CNRS 5205 , Université Claude Bernard Lyon 1,
Université de Lyon, F-69622 , France*

September 23, 2014

Abstract

Let $k \geq 2$ be an integer and T_1, \dots, T_k be spanning trees of a graph G . If for any pair of vertices (u, v) of $V(G)$, the paths from u to v in each T_i , $1 \leq i \leq k$, do not contain common edges and common vertices, except the vertices u and v , then T_1, \dots, T_k are completely independent spanning trees in G . For $2k$ -regular graphs which are $2k$ -connected, such as the Cartesian product of a complete graph of order $2k - 1$ and a cycle and some Cartesian products of three cycles (for $k = 3$), the maximum number of completely independent spanning trees contained in these graphs is determined and it turns out that this maximum is not always k .

Keywords: Spanning tree, Cartesian product, Completely independent spanning tree.

1 Introduction

Let $k \geq 2$ be an integer and T_1, \dots, T_k be spanning trees in a graph G . The spanning trees T_1, \dots, T_k are *edge-disjoint* if $E(T_1) \cap \dots \cap E(T_k) = \emptyset$. For a given tree T and a given pair of vertices (u, v) of T , let $P_T(u, v)$ be the set of vertices in the unique path between u and v in T . The spanning trees T_1, \dots, T_k are *internally disjoint* if for any pair of vertices (u, v) of $V(G)$, $P_{T_1}(u, v) \cap \dots \cap P_{T_k}(u, v) = \{u, v\}$. Finally, the spanning trees T_1, \dots, T_k are *completely independent spanning trees* if they are pairwise edge disjoint and internally disjoint.

*Author partially supported by the Burgundy Council

Disjoint spanning trees have been extensively studied as they are of practical interest for fault-tolerant broadcasting or load-balancing communication systems in interconnection networks : a spanning-tree is often used in various network operations; computing completely independent spanning-trees guarantees a continuity of service, as each can be immediately used as backup spanning tree if a node or link failure occurs on the current spanning tree. Thus, computing k completely independent spanning trees allows to handle up to $k - 1$ simultaneous independent node or link failures. In this context, a network is often modeled by a graph G in which the set of vertices $V(G)$ corresponds to the nodes set and the set of edges $E(G)$ to the set of direct links between nodes.

Completely independent spanning trees were introduced by T. Hasunuma [4] and then have been studied on different classes of graphs, such as underlying graphs of line graphs [4], maximal planar graphs [6], Cartesian product of two cycles [7] and complete graphs, complete bipartite and tripartite graphs [11]. Moreover, the decision problem that consists in determining if there exist two completely independent spanning trees in a graph G is NP-hard [6].

Other works on disjoint spanning trees include independent spanning trees which focus on finding spanning trees T_1, \dots, T_k rooted at r , such that for any vertex v the paths from r to v in T_1, \dots, T_k are pairwise openly disjoint. the main difference is that T_1, \dots, T_k are rooted at r and only the paths to r are considered. Thus T_1, \dots, T_k may share common edges, which is not admissible with completely independent spanning trees. Independent spanning trees have been studied in several topologies, including product graphs [10], de Bruijn and Kautz digraphs [3, 5], and chordal rings [9]. Related works also include Edge-disjoint spanning trees, i.e. spanning-trees which are pairwise edge disjoint only. Edge-disjoint spanning trees have been studied on many classes of graphs, including hypercubes [1], Cartesian product of cycles [2] and Cartesian product of two graphs [8].

We use the following notations : for a tree, a vertex that is not a leaf is called an *inner vertex*. For a vertex u of a graph G , let $d_G(u)$ be its degree in G , i.e. the number of edges of G incident with it.

For clarity, we recall the definition of the Cartesian product of two graphs : Given two graphs G and H , the Cartesian product of G and H , denoted $G \square H$, is the graph with vertex set $V(G) \times V(H)$ and edge set $\{(u, u')(v, v') | (u = v \wedge u'v' \in E(H)) \vee (u' = v' \wedge uv \in E(G))\}$.

The following theorem gives an alternative definition [4] of completely independent spanning trees.

Theorem 1.1 ([4]). *Let $k \geq 2$ be an integer. T_1, \dots, T_k are completely independent spanning trees in a graph G if and only if they are edge-disjoint spanning trees of G and for any $v \in V(G)$, there is at most one T_i such that $d_{T_i}(v) > 1$.*

It has been conjectured that in any $2k$ -connected graph, there are k completely independent spanning trees [6]. This conjecture has been refuted, as there exist $2k$ -connected graphs which do not contain two completely independent spanning trees [12], for any integer k . However, the given counterexamples are not $2k$ -regular.

Proposition 1.2 ([12]). *For any $k \geq 2$, there exist $2k$ -connected graphs that do not contain two completely independent spanning trees.*

The proof of the previous proposition consists in constructing a $2k$ -connected graph with a large proportion of vertices of degree $2k$ adjacent to the same vertices and proving that these vertices of degree $2k$ can not be all adjacent to inner vertices in a fixed tree.

This article is organized as follows. Section 2 presents necessary conditions on $2r$ -regular graphs in order to have r completely independent spanning trees. Section 3 presents the maximum number of completely independent spanning trees in $K_m \square C_n$, for $n \geq 3$ and $m \geq 3$. In particular, we exhibit the first $2r$ -regular graphs which are $2r$ -connected and which do not contain r completely independent spanning trees. In Section 4, we determine three completely independent spanning trees in some Cartesian products of three cycles $C_{n_1} \square C_{n_2} \square C_{n_3}$, for $3 \leq n_1 \leq n_2 \leq n_3$.

2 Necessary conditions on $2r$ -regular graphs

Proposition 2.1. *If in a $2r$ -regular graph G there exist r completely independent spanning trees, then every spanning tree has maximum degree at most $r+1$.*

Proof. By Theorem 1.1, every vertex should be of degree 1 in every spanning tree except in one spanning tree. Hence, in a spanning tree, a vertex is either of degree 1 (a leaf) or has degree between 2 and $r+1$ (an inner vertex), as $2r - (r-1) = r+1$. \square

Let $IN(T)$ be the set of inner vertices in a tree T .

Proposition 2.2. *If in a $2r$ -regular graph G of order n there exist r completely independent spanning trees, then there exists a spanning tree T among them such that $|IN(T)| \leq \lfloor n/r \rfloor$.*

Proof. Let T_1, \dots, T_r be completely independent spanning trees in G and suppose that $|IN(T_i)| > \lfloor n/r \rfloor$ for every $i \in \{1, \dots, r\}$. By Theorem 1.1, we have $\sum_{i=1}^r |IN(T_i)| \leq n$. With our hypothesis, we have $\sum_{i=1}^r |IN(T_i)| \geq (\lfloor n/r \rfloor + 1)r > n$, and a contradiction. \square

Proposition 2.3. *If in a $2r$ -regular graph G of order n there exist r completely independent spanning trees T_1, \dots, T_r , then for every integer i , $1 \leq i \leq r$,*

$$\left\lceil \frac{n-2}{r} \right\rceil \leq |IN(T_i)| \leq n - \left\lceil \frac{n-2}{r} \right\rceil (r-1).$$

Proof. In a spanning tree T of a graph of order n we recall that $\sum_{v \in V(T)} d_T(v) = 2n - 2$. By Proposition 2.1, we have $\sum_{v \in V(T)} d_T(v) \leq |IN(T)|r + n$ and we obtain $\lceil \frac{n-2}{r} \rceil \leq |IN(T)|$. By Theorem 1.1, $\sum_{i=1}^r |IN(T_i)| \leq n$. For a fixed integer i , using the previous inequality, we obtain $|IN(T_i)| \leq n - \lceil \frac{n-2}{r} \rceil(r-1)$. \square

Definition 2.1. Let G be a $2r$ -regular graph of order n for which there exist r completely independent spanning trees T_1, \dots, T_r . A lost edge is an edge of G that is in none of the spanning trees T_1, \dots, T_r . We let E^l be the set of lost edges, i.e. $E^l = E(G) - \bigcup_{1 \leq i \leq r} E(T_i)$. Let also $E_{T_i}^l = \{uv \in E(G) \mid u, v \in IN(T_i), uv \notin E(T_i)\}$, for $i \in \{1, \dots, r\}$, i.e. $E_{T_i}^l$ is the subset of edges of E^l that have their two extremities in $IN(T_i)$.

Proposition 2.4. If in a $2r$ -regular graph G of order n there exist r completely independent spanning trees T_1, \dots, T_r , then $|E^l| = r$.

Proof. We have $\sum_{i=1}^r |E(T_i)| + |E^l| = E(G) = rn$ and $\sum_{i=1}^r |E(T_i)| = r(n-1)$. Hence, $|E^l| = r$. \square

Since each edge of $E_{T_i}^l$ is also in E^l and each edge of E^l is in at most one set $E_{T_i}^l$ for some integer i , we have the following observation.

Observation 2.5. In a $2r$ -regular graph G of order n for which there exist r completely independent spanning trees T_1, \dots, T_r , we have $\sum_{1 \leq i \leq r} |E_{T_i}^l| \leq |E^l| = r$.

Definition 2.2. The potential extra degree of a spanning tree T in a $2r$ -regular graph G of order n is $\text{ped}(T) = |IN(T)|r - n + 2$.

With Proposition 2.3, we have the following easy observation:

Observation 2.6. Let G be a graph, for which there exist r completely independent spanning trees T_1, \dots, T_r . Then, for every i , $0 \leq i \leq r$, $\text{ped}(T_i) \geq 0$.

Note also that, by definition, the number of inner vertices of T_i of degree at most r is bounded by $\text{ped}(T_i)$.

Proposition 2.7. If in a $2r$ -regular graph G of order n there exist r completely independent spanning trees, then there exists a spanning tree T among them such that $\text{ped}(T) \leq 2$ and $E_T^l \leq 1$, with strict inequalities if r does not divide n .

Proof. By Proposition 2.2, there exists a tree T among them such that $|IN(T)| \leq \lfloor n/r \rfloor$. Hence, $\text{ped}(T) \leq \lfloor n/r \rfloor r - n + 2 \leq 2$, with strict inequality if r does not divide n . For every edge uv in E_T^l , both u and v are adjacent to one inner vertex of every spanning tree other than T . Hence, both u and v have degree at most r in T and thus $\text{ped}(T) \geq 2|E_T^l|$. \square

Note that the inequality $\text{ped}(T) \geq 2|E_T^l|$ can be strict.

Corollary 2.8. *Suppose that G is a $2r$ -regular graph of order n for which there exist r completely independent spanning trees T_1, \dots, T_r , for $r \geq 3$ and $n \equiv 0 \pmod{r}$. Then, for every integer i , $1 \leq i \leq r$, $|\text{IN}(T_i)| = n/r$ and $\text{ped}(T_i) = 2$.*

Observation 2.9. *For a $2r$ -regular graph G of order n for which there exist r completely independent spanning trees T_1, \dots, T_r , for every tree T_i , $1 \leq i \leq r$, and every edge e in $E_{T_i}^l$, the extremities of e have degree at most r in T_i .*

3 Cartesian product of a complete graph and a cycle

Let $m \geq 3$ and $n \geq 2$ be integers. In this section, the considered graphs are $K_m \square P_n$, and $K_m \square C_n$ $n \geq 3$.

Let $V(K_m \square P_n) = V(K_m \square C_n) = \{u_i^j, 0 \leq i \leq m-1, 0 \leq j \leq n-1\}$ and $E(K_m \square P_n) = \{u_i^j u_k^j, 0 \leq i, k \leq m-1, i \neq k, 0 \leq j \leq n-1\} \cup \{u_i^j u_i^{j+1}, 0 \leq i \leq m-1, 0 \leq j \leq n-2\}$. $E(K_m \square C_n) = E(K_m \square P_n) \cup \{u_i^0 u_i^{n-1}, 0 \leq i \leq m-1\}$.

For $j \in \{0, \dots, n-1\}$, the subgraphs K^j induced by $\{u_i^j, 0 \leq i \leq m-1\}$ are thus complete graphs on m vertices that we call K -copies. In order to study the distribution of inner vertices of the spanning trees among the K -copies, we let $V_j(T) = \text{IN}(T) \cap V(K^j)$ and $n_j(T) = |V_j(T)|$ for any spanning tree T of $K_m \square C_n$.

In the remaining, the subscript of u_i^j is considered modulo m and its superscript and the subscripts of $V_j(T)$ and $n_j(T)$ are considered modulo n .

Proposition 3.1. *Let n and r be integers, $n \geq 2$, $r \geq 2$. There exist r completely independent spanning trees in $K_{2r} \square P_n$.*

Proof. We construct r completely independent spanning trees T_1, \dots, T_r as follows: $E(T_i) = \{u_{i-1}^j u_{i-1}^{j+1}, u_{r+i-1}^j u_{r+i-1}^{j+1} | j \in \{0, \dots, n-2\}\} \cup \{u_{i-1}^0 u_{r+i-1}^0\} \cup \{u_{i-1}^j u_{i+k}^j, u_{r+i-1}^j u_{r+i+k}^j | k \in \{0, \dots, r-2\}, j \in \{0, \dots, n-1\}\}$. \square

Corollary 3.2. *Let n and r be integers, $n \geq 3$, $r \geq 2$. There exist r completely independent spanning trees in $K_{2r} \square C_n$.*

In the three next propositions, we will prove that there do not exist r completely independent spanning trees in $K_{2r-1} \square C_n$, for some integers r and n . Let $p = |V(K_{2r-1} \square C_n)| = n(2r-1)$ and assume that there exist r completely independent spanning trees T_1, \dots, T_r in $K_{2r-1} \square C_n$. Let T be the spanning tree among them which minimizes $|\text{IN}(T)|$, i.e. $\text{ped}(T)$. By Proposition 2.2, T is such that $|\text{IN}(T)| \leq \lfloor p/r \rfloor = 2n - \lceil n/r \rceil$, $\text{ped}(T) \leq 2nr - \lceil n/r \rceil r - p + 2 \leq n - \lceil n/r \rceil r + 2 \leq 2$ and $|E_T^l| \leq 1$. In order to establish this property we will consider all possible distributions of inner vertices of T among the different K -copies and prove that for each of them we have a contradiction.

The properties given in the following lemma will be useful.

Lemma 3.3. *Let $a_i(T)$ be the number of K -copies which contains exactly i inner vertices of T . The distribution of inner vertices among the different K -copies is such that:*

- i) *if $n_j(T) \geq k$, for some integer j , then $|E_T^l| \geq \frac{1}{2}(k-1)(k-2)$;*
- ii) *$n_j(T) < 4$, for every integer j ;*
- iii) *$a_3(T) \leq 1$;*
- iv) *if $a_3(T) = 1$, then $n \equiv 0 \pmod{r}$ and $n \geq r$;*
- v) *if $a_0(T) = 0$, then $a_3(T) \leq a_1(T) - \lceil n/r \rceil$; in particular $a_1(T) > a_3(T)$ and $a_1(T) \geq \lceil n/r \rceil$.*

Proof. i) : A complete graph of order k contains $\frac{1}{2}k(k-1)$ edges and only $k-1$ edges are in $E(T)$. Thus we have $|E_T^l| \geq \frac{1}{2}(k-1)(k-2)$.

ii) and iii) : If $n_j(T) \geq 4$ for some j or $a_3(T) > 1$, then by i), we have $|E_T^l| \geq 2$. Hence, a contradiction.

iv) : As $\text{ped}(T) \leq n - \lceil n/r \rceil r + 2$, we have $|E_T^l| < 1$ in the case $n \not\equiv 0 \pmod{r}$. As $n > 0$, we have $n \geq r$.

v) : By ii), we have $|\text{IN}(T)| = a_1(T) + 2a_2(T) + 3a_3(T)$ and $a_2 = n - a_1(T) - a_3(T)$. Hence $|\text{IN}(T)| = a_1(T) + 2(n - a_1(T) - a_3(T)) + 3a_3(T) \leq 2n - \lceil n/r \rceil$ by the choice of T . Thus, $a_3(T) \leq a_1(T) - \lceil n/r \rceil$ and consequently $a_1(T) > a_3$ and $a_1(T) \geq \lceil n/r \rceil$. \square

We recall the following observation used in [12].

Observation 3.4 ([12]). *If in a graph G there exist r completely independent spanning trees T_1, \dots, T_r , then for every integer i , $1 \leq i \leq r$, every vertex is adjacent to an inner vertex of T_i .*

Proposition 3.5. *Let n, r be integers, with $n \geq 3$ and $r \geq 6$. There do not exist r completely independent spanning trees in $K_{2r-1} \square C_n$.*

Proof. The proof is by contradiction, using Properties i)-v) of Lemma 3.3. Suppose that there exist r completely independent spanning trees in $K_{2r-1} \square C_n$ and let T be the tree from Proposition 2.2. If a K -copy K^i , $1 \leq i \leq n$, contains no inner vertex, then, by Observation 3.4, $n_{i-1}(T) + n_{i+1}(T) \geq 2r - 1 \geq 11$. Consequently, we have $n_{i-1}(T) \geq 6$ or $n_{i+1}(T) \geq 6$, contradicting Property ii). Hence $a_0(T) = 0$.

By Property v), $a_1(T) \geq \lceil n/r \rceil \geq 1$. Hence there exists an integer i , $0 \leq i \leq n-1$, such that $n_i = 1$. Let u be the (unique) vertex of $V_i(T)$. The vertex u has degree at most $r+1$ in T and is adjacent in T to a vertex of $V_{i-1}(T) \cup V_{i+1}(T)$. Then, u is adjacent in T to at most r vertices of $V(K^i)$. Thus, at least $r-2 \geq 4$ vertices are not adjacent in T to u . Hence, these $r-2$ vertices are adjacent in T to vertices of $V_{i-1}(T) \cup V_{i+1}(T)$ and consequently $n_{i-1}(T) + n_{i+1}(T) \geq 5$. Therefore, we have $n_{i-1}(T) \geq 3$ or $n_{i+1}(T) \geq 3$.

Assume, without loss of generality, that $n_{i+1}(T) \geq 3$. By Property ii), $n_{i+1}(T) = 3$ and by Property iii), $a_3(T) = 1$, i.e., $n_j(T) < 3$ for any $j \neq i$.

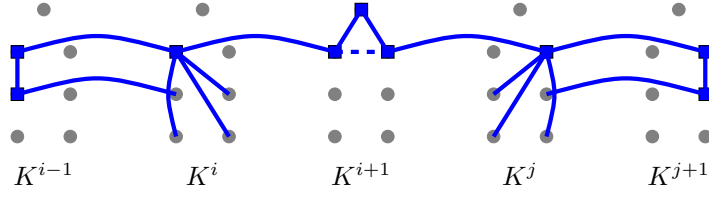


Figure 1: A configuration of inner vertices in the proof of Proposition 3.6. Boxes are inner vertices and the dashed edge represents a lost edge.

But, by Property iv), $n \geq r$ and by Property v), $a_1 \geq 2$. Let j be such that $n_j(T) = 1$, with $j \neq i$. Using a similar argument than above, we obtain that $n_{j-1}(T) \geq 3$ or $n_{j+1}(T) \geq 3$. But, as $a_3(T) = 1$, the only possibility is to have $j = i + 2$, i.e. both K -copies with one internal vertices are adjacent to the same K -copy with three internal vertices.

Let v be the (unique) vertex of $V_j(T)$. One vertex among u and v is adjacent in T to two inner vertices (if not T would be not connected). Suppose, without loss of generality, that u is adjacent in T to two inner vertices. Then u is adjacent in T to at most $r - 1$ vertices in $V(K^i)$. Thus, at least $r - 1 \geq 5$ vertices are not adjacent in T to u . Therefore, at least 5 vertices are adjacent in T to vertices of $V_{i-1}(T) \cup V_{i+1}(T)$ and consequently $n_{i-1}(T) + n_{i+1}(T) \geq 7$. Hence, we have $n_{i-1}(T) \geq 4$ or $n_{i+1}(T) \geq 4$, contradicting Property ii). \square

Proposition 3.6. *Let n, r be integers, with $4 \leq r \leq 5$ and $n \geq r + 1$. There do not exist r completely independent spanning trees in $K_{2r-1} \square C_n$.*

Proof. The proof is by contradiction, using Properties i)-v) of Lemma 3.3. Suppose that there exist r completely independent spanning trees in $K_{2r-1} \square C_n$ and let T be the tree from Proposition 2.2. If a K -copy K^i , $0 \leq i \leq n - 1$, contains no inner vertex, then $n_{i-1}(T) + n_{i+1}(T) \geq 7$. Consequently, we have $n_{i-1}(T) \geq 4$ or $n_{i+1}(T) \geq 4$, contradicting Property ii). Hence $a_0(T) = 0$. By Property v), $a_1(T) \geq \lceil n/r \rceil \geq 2$. Thus, there exist two integers i and j , $0 \leq i \leq j \leq n - 1$, such that $n_i(T) = n_j(T) = 1$, with $u \in V_i(T)$ and $v \in V_j(T)$.

First, suppose that $i = j - 1$. Each of u and v has degree at most $r + 1$ in T and u (v , respectively) is adjacent in T to a vertex of $V_{i-1}(T) \cup V_{i+1}(T)$ (of $V_{j-1}(T) \cup V_{j+1}(T)$, respectively).

If u and v are adjacent in T , then one vertex among u and v is adjacent in T to a vertex of $V_{i-1}(T) \cup V_{j+1}(T)$ (if not T would be not connected). Suppose, without loss of generality, that u is adjacent to two inner vertices. Then, at least $r - 1 \geq 3$ vertices of $V(K^i)$ are not adjacent in T to u . Consequently, $n_{i-1}(T) \geq 4$ and we have a contradiction with Property ii).

Else if u and v are not adjacent in T , then both u and v are adjacent in T to vertices of $V_{i-1}(T) \cup V_{j+1}(T)$ (if not, T would be not connected). The vertices u and v are each adjacent in T to at most r vertices in $V(K^i) \cup V(K^j)$. Hence,

there remain at least $4r - 2 - 2r - 2 = 2r - 4 \geq 4$ vertices in $V(K^i) \cup V(K^j)$ that must be adjacent in T to vertices of $V_{i-1}(T) \cup V_{j+1}(T)$ other than the neighbors of u and of v . Consequently $n_{i-1}(T) + n_{j+1}(T) \geq 6$. Hence, we have $n_{i-1}(T) \geq 3$ and $n_{j+1}(T) \geq 3$, contradicting Property iii) or $n_{i-1}(T) \geq 4$ or $n_{j+1}(T) \geq 4$, contradicting Property ii).

Second, if $|i - j| > 1$, then one vertex among u and v is adjacent in T to two inner vertices (if not T would be not connected). Suppose, without loss of generality, that u is adjacent to two inner vertices. At least $r - 1$ vertices of $V(K^i)$ are not adjacent in T to u . Hence, if $r = 5$, we have $n_{i-1}(T) \geq 3$ and $n_{i+1}(T) \geq 3$, contradicting Property iii) or $n_{i-1}(T) \geq 4$ or $n_{i+1}(T) \geq 4$, contradicting Property ii). Consequently, we suppose that $r = 4$. Then, at least $r - 1 \geq 3$ vertices of $V(K^i)$ are not adjacent in T to u . Therefore, we have $n_{i-1}(T) \geq 3$ or $n_{i+1}(T) \geq 3$.

Assume, without loss of generality, that $n_{i+1}(T) \geq 3$. By Property ii), $n_{i+1}(T) = 3$ and by Property iii), $a_3(T) = 1$, i.e., $n_j(T) < 3$ for any $j \neq i$. But, as $n > r$ and by Property v), $a_1 \geq 3$. Let i' be such that $n_{i'}(T) = 1$, with $i' \neq i$ and $i' \neq i$. If $|i' - i| = 1$ or $|i' - j| = 1$, we have a contradiction, using the first point. Two vertices among u , v and u' should be adjacent to two inner vertices. Suppose it is the vertices u and v . Using a similar argument than above, we obtain that $n_{j-1}(T) \geq 3$ or $n_{j+1}(T) \geq 3$. But, as $a_3(T) = 1$, the only possibility is to have $j = i + 2$, i.e. both K -copies with one internal vertices are adjacent to the same K -copy with three internal vertices.

In this case, as $r = 4$, then four vertices are not inner vertices in $V(K^{i+1})$, at least three vertices of $V(K^i)$ are not adjacent in T to u and at least three vertices of $V(K^j)$ are not adjacent in T to v . Moreover, we have $n_{i-1}(T) \leq 2$ and $n_{j+1}(T) \leq 2$. Figure 1 illustrates this configuration. Thus, four vertices of $V(K^{i+1})$ are adjacent in T to vertices of $V_{i+1}(T)$ and four vertices of $V(K^i) \cup V(K^j)$ are adjacent in T to vertices of $V_{i+1}(T)$. However, by Observation 2.9, the vertices of $V_{i+1}(T)$ can be adjacent to at most seven leaves in T . Hence, we have a contradiction. \square

Proposition 3.7. *There do not exist five completely independent spanning trees in $K_9 \square C_3$.*

Proof. Suppose that there exist five completely independent spanning trees in $K_9 \square C_3$ and let T be the tree from Proposition 2.2. We recall that $|V(K_9 \square C_3)| = 27$ and $|\text{IN}(T)| \leq 6 - \lceil 3/4 \rceil = 5$. If a K -copy K^i , $0 \leq i \leq n - 1$, contains no inner vertex, then $n_{i-1}(T) \geq 5$ or $n_{i+1}(T) \geq 5$. Thus, we have a contradiction with Property ii). By property iv), as $n \not\equiv 0 \pmod{r}$, we have $a_3(T) = 0$. Thus, the only possible distribution of inner vertices of T is $a_1(T) = 1$ and $a_2(T) = 2$. Without loss of generality, suppose that $n_0(T) = 1$, $n_1(T) = 2$ and $n_2(T) = 2$, with $u \in V_1(T)$.

Let the position of a vertex u_i^j be i . As T should be connected, two pairs of inner vertices in different K -copies should be adjacent in T among these five inner vertices. Thus, these five vertices have only three different positions. The

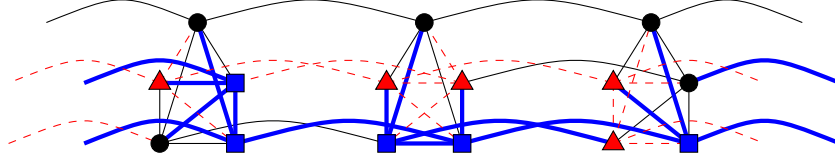


Figure 2: A pattern to have three completely independent spanning trees in $K_5 \square C_n$, for $n \equiv 0 \pmod{3}$.

vertex u has degree at most 6 in T . Hence, there are $r-2 \geq 3$ vertices of $V(K^1)$ not adjacent in T to u . As the inner vertices have only two positions different from the position of u , it is impossible that every vertex is adjacent in T to an inner vertex of T . \square

We now show positive results for the remaining values of r and n . Some of the spanning trees were found using a computer to solve an ILP formulation of the problem.

Proposition 3.8. *Let $n \geq 3$ be an integer such that $n \equiv 0 \pmod{3}$. There exist three completely independent spanning trees in $K_5 \square C_n$.*

Proof. We construct three completely independent spanning trees T_1 , T_2 and T_3 using repeatedly the pattern illustrated in Figure 2 on each three consecutive K -copies:

$$\begin{aligned}
 E(T_1) &= \{u_0^{3j} u_0^{1+3j}, u_0^{1+3j} u_0^{2+3j}, u_0^{2+3j} u_0^{3+3j}, u_0^{3j} u_2^{3j}, u_0^{3j} u_3^{3j}, \\
 &u_3^{3j} u_1^{3j}, u_3^{3j} u_4^{3j}, u_3^{3j} u_3^{1+3j}, u_0^{1+3j} u_1^{1+3j}, u_0^{1+3j} u_4^{1+3j}, u_2^{1+3j} u_2^{2+3j}, \\
 &u_0^{2+3j} u_2^{2+3j}, u_0^{2+3j} u_1^{2+3j}, u_2^{2+3j} u_3^{2+3j}, u_2^{2+3j} u_4^{2+3j} | j \in \{0, \dots, n/3-1\} \} - \{u_0^0, u_0^1\}; \\
 E(T_2) &= \{u_1^{3j} u_1^{1+3j}, u_1^{1+3j} u_1^{2+3j}, u_1^{2+3j} u_1^{3+3j}, u_1^{3j} u_0^{3j}, u_1^{3j} u_4^{3j}, \\
 &u_2^{3j} u_2^{1+3j}, u_1^{1+3j} u_2^{1+3j}, u_1^{1+3j} u_4^{1+3j}, u_2^{1+3j} u_3^{1+3j}, u_2^{1+3j} u_3^{2+3j}, \\
 &u_1^{2+3j} u_2^{2+3j}, u_3^{2+3j} u_0^{2+3j}, u_3^{2+3j} u_4^{2+3j}, u_3^{2+3j} u_3^{3+3j} | j \in \{0, \dots, n/3-1\} \} - \{u_1^0, u_1^1\}; \\
 E(T_3) &= \{u_4^{3j} u_4^{1+3j}, u_4^{1+3j} u_4^{2+3j}, u_4^{2+3j} u_4^{3+3j}, u_2^{3j} u_4^{3j}, u_2^{3j} u_1^{3j}, \\
 &u_2^{3j} u_3^{3j}, u_4^{3j} u_0^{3j}, u_3^{1+3j} u_4^{1+3j}, u_3^{1+3j} u_0^{1+3j}, u_3^{1+3j} u_1^{1+3j}, u_4^{1+3j} u_2^{1+3j}, \\
 &u_3^{1+3j} u_3^{2+3j}, u_4^{2+3j} u_0^{2+3j}, u_4^{2+3j} u_1^{2+3j}, u_2^{2+3j} u_2^{3+3j} | j \in \{0, \dots, n/3-1\} \} - \{u_4^0, u_4^1\}.
 \end{aligned}$$

\square

Proposition 3.9. *Let $n \geq 3$ be an integer. There exist three completely independent spanning trees in $K_5 \square C_n$.*

Proof. By Proposition 3.8, there exist three completely independent spanning trees in $K_5 \square C_n$, for $n \equiv 0 \pmod{3}$. For $n \equiv 1 \pmod{3}$, we use the pattern from Proposition 3.8 for $K^4 \cup \dots \cup K^{n-1}$, completed by the pieces of three completely independent spanning trees of $K^0 \cup K^1 \cup K^2 \cup K^3$ depicted in Figure 3 and whose edge sets are given in Appendix A.1. For $n \equiv 2 \pmod{3}$, we use the pattern from Proposition 3.8 for $K^5 \cup \dots \cup K^{n-1}$, completed by the pieces of three

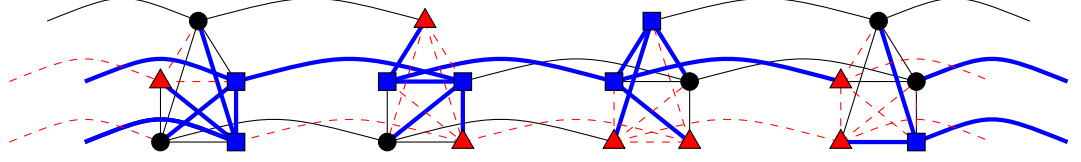


Figure 3: The three completely independent spanning trees in $K_5 \square C_n$, for $K^0 \cup K^1 \cup K^2 \cup K^3$ and $n \equiv 1 \pmod{3}$.

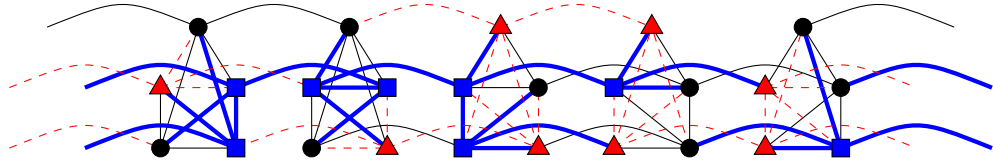


Figure 4: The three completely independent spanning trees in $K_5 \square C_n$, for $K^0 \cup K^1 \cup K^2 \cup K^3 \cup K^4$ and for $n \equiv 2 \pmod{3}$.

completely independent spanning trees of $K^0 \cup K^1 \cup K^2 \cup K^3 \cup K^4$ depicted in Figure 4 and whose edge sets are given in Appendix A.2. Note that Figures 3 and 4 depict also three completely independent spanning trees in $K_5 \square C_4$ and $K_5 \square C_5$. \square

Proposition 3.10. *There exist four completely independent spanning trees in $K_7 \square C_3$.*

Proof. The four completely independent spanning trees in $K_7 \square C_3$ are depicted in Figure 5 and their edge sets are given in Appendix A.3. \square

Proposition 3.11. *There exist four completely independent spanning trees in $K_7 \square C_4$.*

Proof. The four completely independent spanning trees in $K_7 \square C_4$ are depicted in Figure 6 and their edge sets are given in Appendix A.4. \square

Proposition 3.12. *There exist five completely independent spanning trees in $K_9 \square C_4$.*

Proof. The five completely independent spanning trees in $K_9 \square C_4$ are depicted in Figure 7 and their edge sets are given in Appendix A.5. \square

Proposition 3.13. *There exist five completely independent spanning trees in $K_9 \square C_5$.*

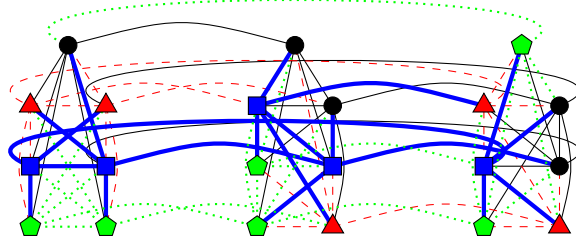


Figure 5: Four completely independent spanning trees in $K_7 \square C_3$.

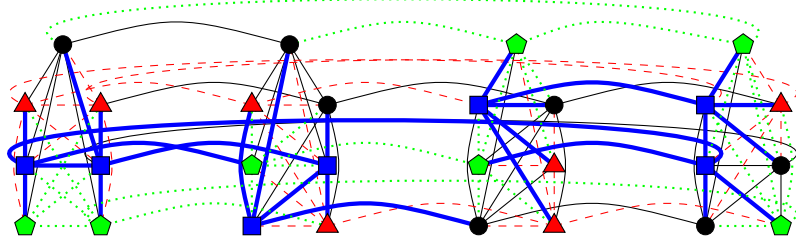


Figure 6: Four completely independent spanning trees in $K_7 \square C_4$.

Proof. The five completely independent spanning trees in $K_9 \square C_5$ are depicted in Figure 8 and their edge sets are given in Appendix A.6. \square

We end this section with a theorem summarizing the results for $K_m \square C_n$. Given a graph G , let $\text{mcist}(G)$ be the maximum integer k such that there exist k completely independent spanning trees in G .

Theorem 3.14. *Let $m \geq 3$ and $n \geq 3$ be integers. We have:*

$$\text{mcist}(K_m \square C_n) = \begin{cases} \lceil m/2 \rceil, & \text{if } (m = 3, 5 \vee (m = 7 \wedge n = 3, 4) \vee (m = 9 \wedge n = 4, 5)); \\ \lfloor m/2 \rfloor, & \text{otherwise.} \end{cases}$$

Proof. For every even m , by Corollary 3.2, there exist $m/2$ completely independent spanning trees. Suppose m is odd. For $m = 3$, Hasunuma and Morisaka [7] has proven that in any Cartesian product of 2-connected graphs, there are two completely independent spanning trees. By Propositions 3.12, 3.13, 3.10, 3.11 and 3.9, we obtain that there exist $\lceil m/2 \rceil$ completely independent spanning trees for $m = 5$ or $(m = 7 \wedge n = 3, 4)$ or $(m = 9 \wedge n = 4, 5)$.

In the other cases, by Propositions 3.5, 3.6, 3.7, there do not exist $\lceil m/2 \rceil$ completely independent spanning trees in these graphs. By Corollary 3.2, there exist $\lfloor m/2 \rfloor$ completely independent spanning trees in $K_{m-1} \square C_n$. From these $\lfloor m/2 \rfloor$ completely independent spanning trees in $K_{m-1} \square C_n$, we can construct $\lfloor m/2 \rfloor$ completely independent spanning trees in $K_m \square C_n$. The graph $K_m \square C_n$ contains n vertices u_0, \dots, u_{n-1} not in $K_{m-1} \square C_n$, with $u_j \in V(K^j)$ for $j =$

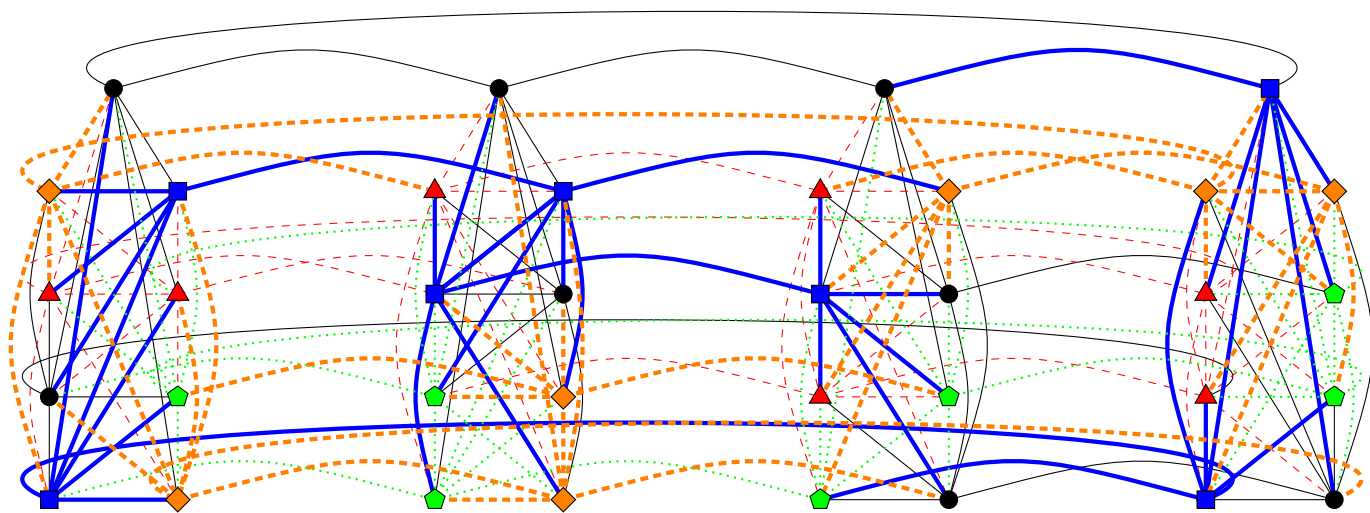


Figure 7: Five completely independent spanning trees in $K_9 \square C_4$.

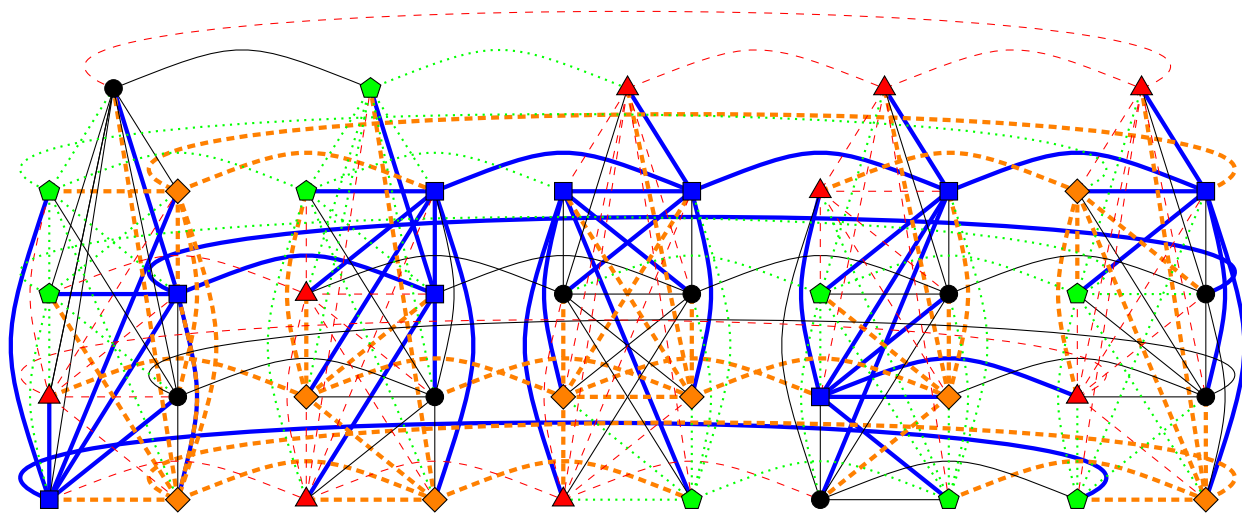


Figure 8: Five completely independent spanning trees in $K_9 \square C_5$.

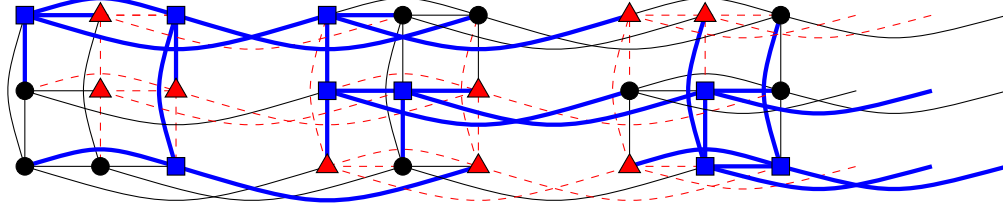


Figure 9: The pattern for the three completely independent spanning trees of $TM(3, 3, 3q)$, with $q \geq 2$.

$0, \dots, n-1$. For each $1 \leq i \leq \lfloor m/2 \rfloor$, it suffices to add an edge between u_j , $1 \leq j \leq n$, and a vertex of $V_j(T_i)$ to obtain $\lfloor m/2 \rfloor$ completely independent spanning trees in $K_m \square C_n$. \square

4 3-dimensional toroidal grids

Hasunuma and Morisaka [7] have shown that there are two completely independent spanning trees in any 2-dimensional toroidal grid and left as an open problem the question of whether there are n completely independent spanning trees in any n -dimensional toroidal grid, for $n \geq 3$. In this section we give a partial answer for $n = 3$ by finding three completely independent spanning trees in some 3-dimensional toroidal grids.

Let n_1 , n_2 and n_3 be positive integers, $3 \leq n_1 \leq n_2 \leq n_3$. The 3-dimensional toroidal grid $TM(n_1, n_2, n_3)$ is the Cartesian product of three cycles: $C_{n_1} \square C_{n_2} \square C_{n_3}$. We let $V(TM(n_1, n_2, n_3)) = \{(i, j, k) | 0 \leq i < n_1, 0 \leq j < n_2, 0 \leq k < n_3\}$ and $E(TM(n_1, n_2, n_3)) = \{(i, j, k) (i', j', k') | i \equiv i' \pm 1 \pmod{n_1}, j = j', k = k' \vee i = i', j \equiv j' \pm 1 \pmod{n_2}, k = k' \vee i = i', j = j', k \equiv k' \pm 1 \pmod{n_3}\}$. In the remainder of the section, the integers i, j and k in a vertex (i, j, k) are considered modulo n_1, n_2 and n_3 , respectively.

By a *level* of $TM(3, 3, q)$ we mean a subgraph of it induced by the vertices with the same third coordinate.

Proposition 4.1. *Let p, p' and q be positive integers such that $\gcd(p, p', q) = 1$. There exist three completely independent spanning trees in $TM(3p, 3p', 3q)$.*

Proof. We define three completely independent spanning trees T_1, T_2 and T_3 in $TM(3p, 3p', 3q)$ as follows: for $j \in \{0, 1, 2\}$,

$$E(T_{j-1}) = \{(i+j, j-i, i)(1+i+j, -i+j, i), (i+j, j-i, i)(i+j, 1-i+j, i), (i+j, j-i, i)(i+j, j-i, 1+i), (i+j, j-i, i)(i+j, -1-i+j, i), (1+i+j, j-i, i)(2+i+j, j-i, i), (1+i+j, j-i, i)(1+i+j, j-i, 1+i), (1+i+j, j-i, i)(1+i, j-i-1, i), (i+j, 1-i+j, i)(1+i+j, 1-i+j, i), (i+j, 1-i+j, i)(i+j, 1-i+j, 1+i) | i \in \{0, \dots, pp'q-1\} - (j, j+1, 0)(j, j+1, -1)\}.$$

We require $\gcd(p, p', q) = 1$, in order that T_1, T_2, T_3 contain every vertex of

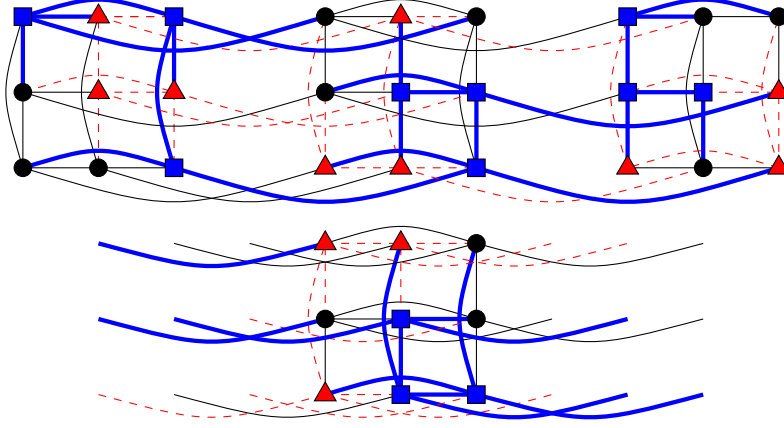


Figure 10: The three completely independent spanning trees on the last four levels of $TM(3, 3, q)$, for $q \equiv 1 \pmod{3}$ and $q > 2$.

$TM(3p, 3p', 3q)$, i.e. every edge is different for each value of i , $0 \leq i \leq pp'q - 1$. Figure 9 describes the pattern on three levels for these three spanning trees for $p = 1$ and $p' = 1$. □

Proposition 4.2. *For any integer $q \geq 3$, there exists three completely independent spanning trees in $TM(3, 3, q)$.*

Proof. First, if $q \equiv 0 \pmod{3}$, then Proposition 4.1 allows us to conclude. For $q \equiv 1 \pmod{3}$ ($q \equiv 2 \pmod{3}$, respectively), we define three completely independent spanning trees by using the pattern of Proposition 4.1 for every level except the last four (five, respectively) ones. If $q \equiv 1 \pmod{3}$, the trees are completed on the last four levels as depicted in Figure 10 (the corresponding edge sets are given in Appendix B.1). If $q \equiv 2 \pmod{3}$, the trees are completed on the last five levels as depicted in Figure 11 (the corresponding edge sets are given in Appendix B.2). □

5 Conclusion

We conclude this paper by listing a few open problems:

1. Determine conditions which ensure that there exist r completely independent spanning trees in a graph.
2. Does any $2r$ -connected graph with sufficiently large girth admit r completely independent spanning trees?

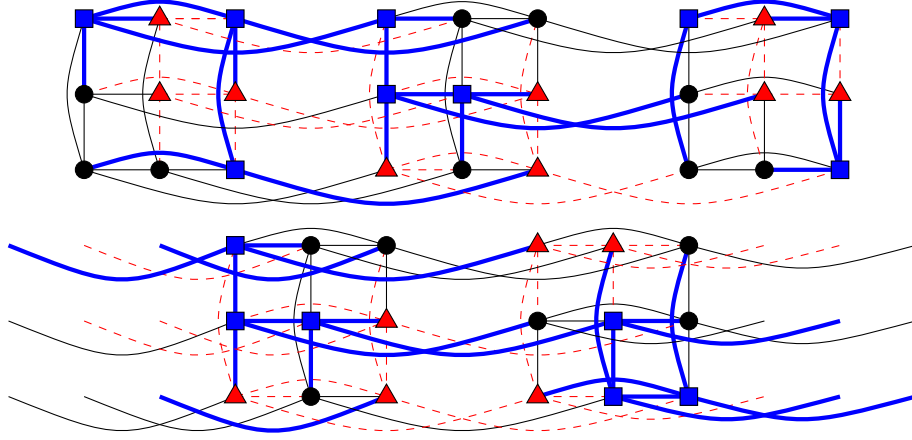


Figure 11: The three completely independent spanning trees on the last five levels of $TM(3, 3, q)$, for $q \equiv 2 \pmod{3}$ and $q > 2$.

3. Is it true that in every 4-regular graph which is 4-connected, there exist 2 completely independent spanning trees?
4. Does the 6-dimensional hypercube $Q_6 = C_4 \square C_4 \square C_4$ admit 3 completely independent spanning trees?

References

- [1] B. Barden, J. Davis, R. Libeskind-Hadas and W. Williams, On edge-disjoint spanning trees in hypercubes, *Information Processing Letters* 70 (1999), 13–16.
- [2] D. M. Blough and H. Wang, Multicast in wormhole-switched torus networks using edge-disjoint spanning trees, *Journal of Parallel and Distributed Computing* 61 (2001), 1278–1306.
- [3] Z. Ge, S.L. Hakimi, Disjoint rooted spanning trees with small depths in de Bruijn and Kautz graphs, *SIAM J. Comput* 26 (1997), 79–92.
- [4] T. Hasunuma, Completely independent spanning trees in the underlying graph of line graph, *Discrete mathematics* 234 (2001), 149–157.
- [5] T. Hasunuma, H. Nagamochi, Independent spanning trees with small depths in iterated line digraphs, *Discrete Applied Mathematics* 110 (2001), 189–211.
- [6] T. Hasunuma, Completely independent spanning trees in maximal planar graphs, *Lecture Notes in Computer Science* 2573 (2002), 235–245.

- [7] T. Hasunuma and C. Morisaka, Completely independent spanning trees in torus networks, *Networks* 60 (2012), 56–69.
- [8] T-K. Hung, S-C. Ku and B-F. Wang, Constructing edge-disjoint spanning trees in product networks, *Parallel and Distributed Systems* 61 (2003), 213–221.
- [9] Y. Iwasaki, Y. Kajiwar, K. Obokata, Y. Igarashi, Independent spanning trees of chordal rings, *Inform. Process. Lett.* 69 (1999), 155–160.
- [10] K. Obokata, Y. Iwasaki, F. Bao, Y. Igarashi, Independent spanning trees in product graphs and their construction, *IEICE Trans.* E79-A (1996), 1894–1903.
- [11] K-J. Pai, S.-M. Tang, J-M. Chang and J-S. Yang, Completely Independent Spanning Trees on Complete Graphs, Complete Bipartite Graphs and Complete Tripartite Graphs, *Advances in Intelligent Systems and Applications* 20 (2013), 107–113.
- [12] F. Péterfalvi, Two counterexamples on completely independent spanning trees. *Discrete mathematics* 312 (2012), 808–810.

A Edge sets of the trees from Section 3

A.1 Three completely independent spanning trees in $K_5 \square C_4$

$$\begin{aligned} E(T_1) &= \{u_0^0 u_3^0, u_0^0 u_2^0, u_3^0 u_1^0, u_3^0 u_4^0, u_3^1 u_1^1, u_3^1 u_4^1, u_2^2 u_1^2, u_2^2 u_4^2, u_3^3 u_2^3, u_3^3 u_3^3, u_2^3 u_1^3, u_2^3 u_4^3, \\ &u_0^0 u_0^0, u_3^0 u_3^0, u_2^1 u_2^1, u_3^1 u_3^1, u_2^2 u_2^2, u_2^2 u_3^2, u_3^2 u_3^2, u_0^3 u_0^3\}; \\ E(T_2) &= \{u_1^0 u_0^0, u_1^0 u_2^0, u_0^1 u_4^1, u_0^1 u_3^1, u_0^1 u_1^1, u_4^1 u_1^1, u_3^2 u_4^2, u_3^2 u_1^2, u_3^2 u_2^2, u_4^2 u_0^2, u_1^3 u_3^3, u_1^3 u_0^3, \\ &u_1^3 u_4^3, u_3^3 u_2^3, u_4^0 u_4^0, u_4^0 u_2^0, u_3^0 u_3^0, u_1^1 u_1^1, u_3^1 u_3^1\}; \\ E(T_3) &= \{u_2^0 u_4^0, u_2^0 u_3^0, u_4^0 u_0^0, u_4^0 u_1^0, u_1^1 u_2^1, u_1^1 u_0^1, u_2^1 u_3^1, u_2^1 u_4^1, u_0^2 u_1^2, u_0^2 u_2^2, u_2^2 u_3^2, u_2^2 u_4^2, \\ &u_4^3 u_0^3, u_4^3 u_3^3, u_2^0 u_1^0, u_1^1 u_1^1, u_2^1 u_2^1, u_3^2 u_2^2, u_3^2 u_4^2\}. \end{aligned}$$

A.2 Three completely independent spanning trees in $K_5 \square C_5$

$$\begin{aligned} E(T_1) &= \{u_0^0 u_3^0, u_0^0 u_2^0, u_3^0 u_1^0, u_3^0 u_4^0, u_0^1 u_1^1, u_0^1 u_2^1, u_0^1 u_4^1, u_3^1 u_1^1, u_2^2 u_2^2, u_2^2 u_1^2, u_2^2 u_4^2, u_3^2 u_3^2, \\ &u_4^3 u_3^3, u_4^3 u_2^3, u_4^3 u_1^3, u_0^4 u_4^4, u_2^4 u_3^4, u_2^4 u_2^4, u_0^0 u_0^0, u_1^1 u_3^1, u_2^2 u_2^2, u_4^2 u_3^2, u_2^2 u_2^2, u_0^4 u_0^4\}; \\ E(T_2) &= \{u_1^0 u_0^0, u_1^0 u_2^0, u_1^1 u_2^1, u_1^1 u_3^1, u_2^0 u_2^0, u_2^0 u_3^0, u_2^1 u_2^1, u_4^2 u_2^2, u_0^3 u_3^3, u_0^3 u_4^3, u_3^3 u_1^3, u_3^3 u_2^3, \\ &u_4^4 u_4^4, u_4^4 u_2^4, u_4^4 u_1^4, u_3^4 u_4^4, u_0^1 u_1^1, u_0^1 u_4^1, u_1^0 u_2^0, u_1^1 u_2^1, u_2^0 u_3^0, u_3^3 u_4^3, u_4^4 u_1^4, u_3^4 u_3^4\}; \\ E(T_3) &= \{u_2^0 u_4^0, u_2^0 u_3^0, u_4^0 u_0^0, u_4^0 u_1^0, u_1^1 u_2^1, u_1^1 u_0^1, u_1^1 u_4^1, u_2^1 u_3^1, u_1^2 u_2^2, u_1^2 u_0^2, u_2^2 u_2^2, u_3^2 u_2^2, \\ &u_3^1 u_0^1, u_3^1 u_2^1, u_4^4 u_4^4, u_4^4 u_3^4, u_2^0 u_2^0, u_1^1 u_1^1, u_2^1 u_2^1, u_3^2 u_3^2, u_3^2 u_4^2, u_4^4 u_4^4, u_2^4 u_2^4, u_4^4 u_4^4\}. \end{aligned}$$

A.3 Four completely independent spanning trees in $K_7 \square C_3$

$$\begin{aligned} E(T_1) &= \{u_0^0 u_1^0, u_0^0 u_3^0, u_0^0 u_5^0, u_0^0 u_6^0, u_0^1 u_1^1, u_0^1 u_4^1, u_0^1 u_5^1, u_2^1 u_1^1, u_2^1 u_3^1, u_2^1 u_6^1, u_2^2 u_2^2, u_2^2 u_5^2, \\ &u_2^2 u_6^2, u_4^3 u_0^3, u_4^3 u_1^3, u_4^3 u_2^3, u_0^4 u_0^4, u_2^4 u_2^4, u_2^4 u_5^4, u_4^4 u_4^4\}; \\ E(T_2) &= \{u_1^0 u_2^0, u_1^0 u_3^0, u_1^0 u_5^0, u_2^0 u_0^0, u_2^0 u_4^0, u_2^0 u_6^0, u_6^1 u_0^1, u_6^1 u_3^1, u_6^1 u_4^1, u_6^1 u_5^1, u_1^2 u_0^2, u_1^2 u_2^2, \\ &u_1^2 u_3^2, u_1^2 u_6^2, u_6^2 u_4^2, u_6^2 u_5^2, u_0^1 u_1^1, u_2^1 u_2^1, u_6^1 u_6^1, u_0^1 u_1^1\}; \\ E(T_3) &= \{u_3^0 u_2^0, u_3^0 u_4^0, u_3^0 u_5^0, u_4^0 u_0^0, u_4^0 u_1^0, u_4^0 u_6^0, u_1^1 u_0^1, u_1^1 u_3^1, u_1^1 u_4^1, u_1^1 u_6^1, u_4^1 u_2^1, u_4^1 u_5^1, \\ &u_3^2 u_0^2, u_3^2 u_2^2, u_3^2 u_5^2, u_3^2 u_6^2, u_0^1 u_4^1, u_1^1 u_2^1, u_4^1 u_2^1, u_0^3 u_3^3\}; \\ E(T_4) &= \{u_5^0 u_2^0, u_5^0 u_4^0, u_5^0 u_6^0, u_6^0 u_0^0, u_6^0 u_3^0, u_3^1 u_0^1, u_3^1 u_4^1, u_3^1 u_5^1, u_3^1 u_1^1, u_3^1 u_2^1, u_0^2 u_2^2, u_0^2 u_5^2, \\ &u_0^2 u_6^2, u_5^2 u_1^2, u_5^2 u_4^2, u_5^2 u_5^2, u_6^2 u_6^2, u_3^2 u_3^2, u_5^2 u_5^2, u_0^0 u_0^0\}. \end{aligned}$$

A.4 Four completely independent spanning trees in $K_7 \square C_4$

$$\begin{aligned} E(T_1) &= \{u_0^0 u_1^0, u_0^0 u_3^0, u_0^0 u_5^0, u_0^0 u_6^0, u_0^1 u_1^1, u_0^1 u_4^1, u_0^1 u_2^1, u_0^1 u_3^1, u_2^1 u_5^1, u_2^1 u_6^1, u_2^2 u_2^2, u_2^2 u_5^2, u_2^2 u_6^2, \\ &u_5^2 u_0^2, u_5^2 u_1^2, u_5^2 u_4^2, u_4^3 u_3^3, u_4^3 u_5^3, u_4^3 u_6^3, u_5^3 u_0^3, u_5^3 u_1^3, u_0^4 u_0^4, u_2^4 u_2^4, u_2^4 u_5^4, u_2^4 u_6^4, u_4^4 u_4^4\}; \\ E(T_2) &= \{u_1^0 u_2^0, u_1^0 u_4^0, u_1^0 u_5^0, u_2^0 u_0^0, u_2^0 u_3^0, u_2^0 u_6^0, u_1^1 u_2^1, u_1^1 u_4^1, u_1^1 u_6^1, u_6^1 u_0^1, u_6^1 u_3^1, u_6^1 u_5^1, u_4^2 u_2^2, \\ &u_4^2 u_3^2, u_4^2 u_6^2, u_6^2 u_0^2, u_6^2 u_5^2, u_3^3 u_0^3, u_3^3 u_3^3, u_3^3 u_4^3, u_3^3 u_5^3, u_0^1 u_1^1, u_1^1 u_2^1, u_6^1 u_6^1, u_6^2 u_6^2, u_0^1 u_1^1, u_2^0 u_2^0\}; \\ E(T_3) &= \{u_3^0 u_4^0, u_3^0 u_1^0, u_3^0 u_5^0, u_4^0 u_0^0, u_4^0 u_2^0, u_4^0 u_6^0, u_4^1 u_2^1, u_4^1 u_5^1, u_4^1 u_6^1, u_5^1 u_0^1, u_5^1 u_1^1, u_1^2 u_0^2, u_1^2 u_2^2, \\ &u_1^2 u_4^2, u_1^2 u_6^2, u_1^3 u_0^3, u_1^3 u_2^3, u_1^3 u_3^3, u_1^3 u_4^3, u_3^3 u_5^3, u_3^3 u_6^3, u_0^3 u_3^3, u_4^0 u_4^0, u_5^1 u_5^1, u_1^2 u_1^2, u_2^3 u_3^3, u_3^0 u_3^0\}; \\ E(T_4) &= \{u_5^0 u_2^0, u_5^0 u_4^0, u_5^0 u_6^0, u_6^0 u_0^0, u_6^0 u_3^0, u_3^1 u_1^1, u_3^1 u_2^1, u_3^1 u_4^1, u_3^1 u_5^1, u_0^2 u_2^2, u_0^2 u_3^2, u_0^2 u_4^2, u_3^2 u_1^2, \\ &u_3^2 u_5^2, u_3^2 u_6^2, u_0^3 u_3^3, u_0^3 u_4^3, u_0^3 u_6^3, u_3^3 u_1^3, u_3^3 u_2^3, u_3^3 u_5^3, u_6^0 u_6^0, u_0^1 u_0^1, u_3^1 u_3^1, u_0^2 u_0^2, u_0^3 u_0^3, u_6^0 u_6^0\}. \end{aligned}$$

A.5 Five completely independent spanning trees in $K_9 \square C_4$

$$\begin{aligned} E(T_1) &= \{u_0^0 u_2^0, u_0^0 u_4^0, u_0^0 u_5^0, u_0^0 u_8^0, u_0^1 u_0^1, u_5^0 u_0^0, u_5^0 u_6^0, u_5^0 u_7^0, u_0^2 u_2^2, u_0^2 u_4^2, u_0^2 u_6^2, u_0^2 u_7^2, u_4^1 u_1^1, \\ &u_4^1 u_5^1, u_4^1 u_8^1, u_0^3 u_3^3, u_0^3 u_4^3, u_0^3 u_6^3, u_4^2 u_2^2, u_4^2 u_5^2, u_4^2 u_8^2, u_8^2 u_2^2, u_8^2 u_5^2, u_8^2 u_7^2, u_8^2 u_1^2, u_8^2 u_3^2, u_8^2 u_6^2, \\ &u_8^2 u_8^2, u_0^4 u_0^4, u_0^4 u_2^4, u_4^3 u_3^3, u_0^5 u_0^5, u_5^3 u_3^3\}; \end{aligned}$$

$$\begin{aligned}
E(T_2) &= \{u_3^0u_0^0, u_3^0u_4^0, u_3^0u_7^0, u_3^0u_8^0, u_4^0u_1^0, u_4^0u_2^0, u_4^0u_5^0, u_4^0u_6^0, u_1^1u_0^1, u_1^1u_2^1, u_1^1u_6^1, u_1^1u_7^1, u_1^1u_8^1, \\
&u_1^2u_0^2, u_1^2u_2^2, u_1^2u_5^2, u_1^2u_7^2, u_1^2u_8^2, u_2^2u_4^2, u_2^2u_5^2, u_3^3u_2^3, u_3^3u_5^3, u_3^3u_6^3, u_3^3u_7^3, u_3^3u_0^3, u_3^3u_1^3, u_3^3u_4^3, u_3^3u_8^3, \\
&u_3^0u_3^1, u_4^0u_4^1, u_1^1u_1^1, u_5^1u_5^1, u_3^2u_3^2, u_5^2u_5^2, u_3^0u_3^3\}; \\
E(T_3) &= \{u_2^0u_1^0, u_2^0u_3^0, u_2^0u_5^0, u_2^0u_7^0, u_7^0u_0^0, u_7^0u_4^0, u_7^0u_6^0, u_7^0u_8^0, u_2^1u_3^1, u_2^1u_4^1, u_2^1u_5^1, u_2^1u_6^1, u_3^1u_0^1, \\
&u_3^1u_1^1, u_3^1u_7^1, u_3^1u_8^1, u_3^2u_1^2, u_3^2u_4^2, u_3^2u_5^2, u_3^2u_6^2, u_6^2u_8^2, u_0^3u_2^3, u_0^3u_3^3, u_0^3u_4^3, u_0^3u_7^3, u_0^3u_8^3, u_7^3u_1^3, u_7^3u_5^3, \\
&u_7^3u_6^3, u_2^0u_2^1, u_2^0u_2^2, u_3^1u_3^2, u_2^2u_0^2, u_7^2u_7^2, u_7^2u_7^3\}; \\
E(T_4) &= \{u_6^0u_0^0, u_6^0u_1^0, u_6^0u_2^0, u_6^0u_3^0, u_6^0u_8^0, u_5^1u_0^1, u_5^1u_1^1, u_5^1u_3^1, u_5^1u_7^1, u_5^1u_8^1, u_7^1u_2^1, u_7^1u_4^1, u_7^1u_6^1, u_7^1u_8^1, \\
&u_6^2u_1^2, u_6^2u_2^2, u_6^2u_4^2, u_6^2u_7^2, u_6^2u_8^2, u_7^2u_0^2, u_7^2u_2^2, u_7^2u_5^2, u_4^3u_2^3, u_4^3u_3^3, u_4^3u_6^3, u_4^3u_7^3, u_4^3u_8^3, u_6^3u_0^3, u_6^3u_1^3, \\
&u_6^3u_5^3, u_5^0u_5^1, u_7^0u_7^1, u_7^0u_7^2, u_6^2u_6^3, u_4^0u_4^3, u_6^0u_6^3\}; \\
E(T_5) &= \{u_1^0u_0^0, u_1^0u_3^0, u_1^0u_7^0, u_1^0u_8^0, u_8^0u_0^0, u_8^0u_4^0, u_8^0u_5^0, u_6^1u_3^1, u_6^1u_4^1, u_6^1u_5^1, u_6^1u_8^1, u_8^1u_1^1, u_8^1u_2^1, \\
&u_8^1u_7^1, u_2^2u_0^2, u_2^2u_3^2, u_2^2u_4^2, u_2^2u_5^2, u_2^2u_7^2, u_3^3u_0^3, u_3^3u_2^3, u_3^3u_3^3, u_3^3u_4^3, u_2^3u_5^3, u_2^3u_6^3, u_2^3u_7^3, u_0^1u_1^1, u_0^1u_6^1, \\
&u_8^0u_8^1, u_6^1u_6^2, u_8^1u_8^2, u_1^2u_1^3, u_2^2u_2^3, u_0^1u_1^3, u_8^0u_8^3\}.
\end{aligned}$$

A.6 Five completely independent spanning trees in $K_9 \square C_4$

$$\begin{aligned}
E(T_1) &= \{u_0^0u_2^0, u_0^0u_3^0, u_0^0u_5^0, u_0^0u_6^0, u_0^0u_7^0, u_6^0u_0^1, u_6^0u_4^0, u_6^0u_8^0, u_6^1u_1^1, u_6^1u_2^1, u_6^1u_5^1, u_6^1u_7^1, u_6^1u_8^1, \\
&u_3^2u_2^2, u_3^2u_1^2, u_3^2u_4^2, u_3^2u_6^2, u_3^2u_8^2, u_2^2u_2^2, u_2^2u_5^2, u_2^2u_7^2, u_4^3u_0^3, u_4^3u_2^3, u_4^3u_3^3, u_4^3u_7^3, u_4^3u_1^3, u_4^3u_5^3, u_7^3u_3^3, \\
&u_4^4u_0^4, u_4^4u_2^4, u_4^4u_6^4, u_4^4u_8^4, u_6^4u_1^4, u_6^4u_3^4, u_6^4u_5^4, u_0^0u_1^0, u_6^0u_6^1, u_1^1u_3^1, u_1^1u_4^1, u_1^1u_7^1, u_1^1u_8^1, u_3^3u_6^3, u_6^3u_7^4, u_6^0u_6^4\}; \\
E(T_2) &= \{u_7^0u_1^0, u_7^0u_2^0, u_7^0u_4^0, u_7^0u_6^0, u_7^0u_8^0, u_3^1u_1^1, u_3^1u_4^1, u_3^1u_6^1, u_3^1u_7^1, u_3^1u_8^1, u_7^1u_0^1, u_7^1u_5^1, u_7^1u_6^1, \\
&u_2^0u_2^1, u_2^0u_4^1, u_0^2u_5^2, u_0^2u_7^2, u_0^2u_8^2, u_7^2u_2^2, u_7^2u_3^2, u_7^2u_6^2, u_0^3u_1^3, u_0^3u_5^3, u_0^3u_8^3, u_1^3u_2^3, u_1^3u_3^3, u_1^3u_4^3, u_1^3u_6^3, \\
&u_0^4u_4^1, u_0^4u_5^1, u_0^4u_6^1, u_0^4u_7^1, u_0^4u_8^1, u_5^2u_2^2, u_5^2u_3^2, u_5^2u_4^2, u_5^2u_8^2, u_3^0u_3^1, u_7^0u_7^1, u_7^0u_7^2, u_6^2u_0^2, u_7^2u_7^2, u_0^0u_0^4, u_5^0u_5^4\}; \\
E(T_3) &= \{u_4^0u_0^0, u_4^0u_3^0, u_4^0u_7^0, u_4^0u_8^0, u_7^0u_0^1, u_7^0u_2^1, u_7^0u_5^1, u_7^0u_6^1, u_7^0u_8^1, u_2^1u_1^1, u_2^1u_3^1, u_2^1u_4^1, u_2^1u_5^1, u_2^1u_6^1, u_2^1u_8^1, \\
&u_4^1u_0^1, u_4^1u_6^1, u_4^1u_7^1, u_4^1u_8^1, u_7^1u_2^1, u_7^1u_4^1, u_7^1u_5^1, u_7^1u_7^1, u_2^2u_2^2, u_2^2u_3^2, u_2^2u_6^2, u_2^2u_7^2, u_2^2u_8^2, u_3^3u_0^3, u_3^3u_2^3, u_3^3u_3^3, u_3^3u_7^3, \\
&u_5^3u_0^3, u_5^3u_1^3, u_5^3u_3^3, u_5^3u_8^3, u_4^2u_0^2, u_4^2u_1^2, u_4^2u_4^2, u_4^2u_8^2, u_4^4u_0^4, u_4^4u_1^4, u_4^4u_2^4, u_4^4u_3^4, u_4^4u_4^4, u_4^4u_5^4, u_4^4u_6^4, u_4^4u_7^4\}; \\
E(T_4) &= \{u_1^0u_0^0, u_1^0u_3^0, u_1^0u_4^0, u_1^0u_8^0, u_3^0u_0^1, u_3^0u_2^1, u_3^0u_5^1, u_3^0u_6^1, u_3^0u_7^1, u_0^1u_1^1, u_0^1u_2^1, u_0^1u_3^1, u_0^1u_4^1, u_0^1u_5^1, u_0^1u_6^1, \\
&u_1^1u_4^1, u_1^1u_7^1, u_1^1u_8^1, u_2^2u_2^2, u_2^2u_4^2, u_2^2u_5^2, u_2^2u_6^2, u_2^2u_7^2, u_3^3u_0^3, u_3^3u_5^3, u_3^3u_7^3, u_3^3u_8^3, u_5^3u_2^3, u_5^3u_3^3, u_5^3u_4^3, \\
&u_8^3u_0^3, u_8^3u_4^3, u_8^3u_7^3, u_8^3u_8^3, u_7^2u_2^2, u_7^2u_4^2, u_7^2u_5^2, u_7^2u_6^2, u_0^4u_0^4, u_0^4u_1^4, u_0^4u_2^4, u_0^4u_3^4, u_0^4u_4^4, u_0^4u_5^4, u_0^4u_6^4, u_0^4u_7^4\}; \\
E(T_5) &= \{u_2^0u_1^0, u_2^0u_4^0, u_2^0u_6^0, u_2^0u_8^0, u_8^0u_0^0, u_8^0u_3^0, u_8^0u_7^0, u_5^1u_1^1, u_5^1u_3^1, u_5^1u_4^1, u_5^1u_8^1, u_1^2u_2^2, u_1^2u_3^2, u_1^2u_6^2, u_1^2u_7^2, u_1^2u_8^2, \\
&u_5^2u_2^2, u_5^2u_3^2, u_5^2u_6^2, u_5^2u_7^2, u_6^2u_0^2, u_6^2u_1^2, u_6^2u_4^2, u_6^2u_8^2, u_3^3u_0^3, u_3^3u_2^3, u_3^3u_3^3, u_3^3u_4^3, u_3^3u_5^3, u_3^3u_6^3, u_3^3u_7^3, u_3^3u_8^3, \\
&u_4^4u_0^4, u_4^4u_1^4, u_4^4u_2^4, u_4^4u_3^4, u_4^4u_4^4, u_4^4u_5^4, u_4^4u_6^4, u_4^4u_7^4, u_2^2u_2^2, u_5^2u_5^2, u_8^2u_8^2, u_5^0u_5^4, u_8^0u_8^4\}.
\end{aligned}$$

B Edge sets of the trees from Section 4

B.1 Three completely independent spanning trees in the last four levels of $TM(3, 3, q)$

$$\begin{aligned}
E(T_1) &= \{(0, 0, 0)(1, 0, 0), (0, 0, 0)(0, 1, 0), (0, 0, 0)(0, 2, 0), (0, 0, 0)(0, 0, 1), \\
&(1, 0, 0)(1, 2, 0), (1, 0, 0)(2, 0, 0), (1, 0, 0)(1, 0, 1), (0, 1, 0)(1, 1, 0), (0, 1, 0)(0, 1, 1), \\
&(0, 1, 1)(1, 1, 1), (0, 1, 1)(0, 2, 1), (0, 1, 1)(0, 1, 2), (0, 2, 1)(1, 2, 1), (0, 2, 1)(2, 2, 1), \\
&(0, 2, 1)(0, 2, 2), (2, 2, 1)(2, 0, 1), (2, 2, 1)(2, 1, 1), (1, 0, 2)(0, 0, 2), (1, 0, 2)(2, 0, 2), \\
&(1, 0, 2)(1, 2, 2), (1, 0, 2)(1, 0, 3), (1, 2, 2)(2, 2, 2), (1, 2, 2)(1, 1, 2), (1, 2, 2)(1, 2, 3), \\
&(2, 2, 2)(2, 1, 2), (2, 2, 2)(2, 2, 3), (0, 1, 3)(1, 1, 3), (0, 1, 3)(0, 0, 3), (0, 1, 3)(2, 1, 3), \\
&(0, 1, 3)(0, 1, 4), (2, 1, 3)(2, 0, 3), (2, 1, 3)(2, 2, 3), (2, 1, 3)(2, 1, 4), (2, 2, 3)(0, 2, 3), \\
&(2, 2, 3)(2, 2, 4)\}; \\
E(T_2) &= \{(1, 1, 0)(2, 1, 0), (1, 1, 0)(1, 0, 0), (1, 1, 0)(1, 2, 0), (1, 1, 0)(1, 1, 1),
\end{aligned}$$

$(2, 1, 0)(0, 1, 0), (2, 1, 0)(2, 0, 0), (2, 1, 0)(2, 1, 1), (1, 2, 0)(2, 2, 0), (1, 2, 0)(1, 2, 1),$
 $(0, 0, 1)(1, 0, 1), (0, 0, 1)(0, 1, 1), (0, 0, 1)(0, 2, 1), (1, 0, 1)(2, 0, 1), (1, 0, 1)(1, 2, 1),$
 $(1, 0, 1)(1, 0, 2), (1, 2, 1)(2, 2, 1), (1, 2, 1)(1, 2, 2), (0, 0, 2)(2, 0, 2), (0, 0, 2)(0, 2, 2),$
 $(0, 0, 2)(0, 0, 3), (2, 0, 2)(2, 1, 2), (2, 0, 2)(2, 2, 2), (2, 0, 2)(2, 0, 3), (2, 1, 2)(0, 1, 2),$
 $(2, 1, 2)(1, 1, 2), (2, 1, 2)(2, 1, 3), (0, 0, 3)(1, 0, 3), (0, 0, 3)(0, 2, 3), (0, 0, 3)(0, 0, 4),$
 $(0, 2, 3)(1, 2, 3), (0, 2, 3)(0, 1, 3), (0, 2, 3)(0, 2, 4), (1, 2, 3)(2, 2, 3), (1, 2, 3)(1, 1, 3),$
 $(1, 2, 3)(1, 2, 4)\};$
 $E(T_3) = \{(2, 0, 0)(0, 0, 0), (2, 0, 0)(2, 2, 0), (2, 0, 0)(2, 0, 1), (0, 2, 0)(1, 2, 0),$
 $(0, 2, 0)(2, 2, 0), (0, 2, 0)(0, 1, 0), (0, 2, 0)(0, 2, 1), (2, 2, 0)(2, 1, 0), (2, 2, 0)(2, 2, 1),$
 $(2, 0, 1)(0, 0, 1), (2, 0, 1)(2, 1, 1), (2, 0, 1)(2, 0, 2), (1, 1, 1)(2, 1, 1), (1, 1, 1)(1, 0, 1),$
 $(1, 1, 1)(1, 2, 1), (2, 1, 1)(0, 1, 1), (2, 1, 1)(2, 1, 2), (0, 1, 2)(1, 1, 2), (0, 1, 2)(0, 0, 2),$
 $(0, 1, 2)(0, 2, 2), (0, 1, 2)(0, 1, 3), (1, 1, 2)(1, 0, 2), (1, 1, 2)(1, 1, 3), (0, 2, 2)(1, 2, 2),$
 $(0, 2, 2)(2, 2, 2), (0, 2, 2)(0, 2, 3), (1, 0, 3)(2, 0, 3), (1, 0, 3)(1, 1, 3), (1, 0, 3)(1, 2, 3),$
 $(1, 0, 3)(1, 0, 4), (2, 0, 3)(0, 0, 3), (2, 0, 3)(2, 2, 3), (2, 0, 3)(2, 0, 4), (1, 1, 3)(2, 1, 3),$
 $(1, 1, 3)(1, 1, 4)\}.$

B.2 Three completely independent spanning trees in the last five levels of $TM(3, 3, q)$

$E(T_1) = \{(0, 0, 0)(1, 0, 0), (0, 0, 0)(0, 1, 0), (0, 0, 0)(0, 2, 0), (0, 0, 0)(0, 0, 1),$
 $(1, 0, 0)(1, 2, 0), (1, 0, 0)(2, 0, 0), (1, 0, 0)(1, 0, 1), (0, 1, 0)(1, 1, 0), (0, 1, 0)(0, 1, 1),$
 $(1, 0, 1)(2, 0, 1), (1, 0, 1)(1, 2, 1), (1, 2, 1)(2, 2, 1), (1, 2, 1)(1, 1, 1), (1, 2, 1)(1, 2, 2),$
 $(2, 2, 1)(0, 2, 1), (2, 2, 1)(2, 1, 1), (2, 2, 1)(2, 2, 2), (0, 0, 2)(1, 0, 2), (0, 0, 2)(2, 0, 2),$
 $(0, 0, 2)(0, 1, 2), (0, 0, 2)(0, 0, 3), (1, 0, 2)(1, 1, 2), (1, 0, 2)(1, 0, 3), (0, 1, 2)(2, 1, 2),$
 $(0, 1, 2)(0, 2, 2), (0, 1, 2)(0, 1, 3), (1, 0, 3)(2, 0, 3), (1, 0, 3)(1, 2, 3), (1, 0, 3)(1, 0, 4),$
 $(1, 2, 3)(2, 2, 3), (1, 2, 3)(1, 1, 3), (1, 2, 3)(1, 2, 4), (2, 2, 3)(0, 2, 3), (2, 2, 3)(2, 1, 3),$
 $(2, 2, 3)(2, 2, 4), (0, 1, 4)(1, 1, 4), (0, 1, 4)(0, 0, 4), (0, 1, 4)(2, 1, 4), (0, 1, 4)(0, 1, 5),$
 $(2, 1, 4)(2, 0, 4), (2, 1, 4)(2, 2, 4), (2, 1, 4)(2, 1, 5), (2, 2, 4)(0, 2, 4), (2, 2, 4)(2, 2, 5)\};$
 $E(T_2) = \{(1, 1, 0)(2, 1, 0), (1, 1, 0)(1, 0, 0), (1, 1, 0)(1, 2, 0), (1, 1, 0)(1, 1, 1),$
 $(2, 1, 0)(0, 1, 0), (2, 1, 0)(2, 0, 0), (2, 1, 0)(2, 1, 1), (1, 2, 0)(2, 2, 0), (1, 2, 0)(1, 2, 1),$
 $(0, 0, 1)(1, 0, 1), (0, 0, 1)(2, 0, 1), (0, 0, 1)(0, 2, 1), (0, 0, 1)(0, 0, 2), (2, 0, 1)(2, 1, 1),$
 $(2, 0, 1)(2, 2, 1), (2, 0, 1)(2, 0, 2), (2, 1, 1)(0, 1, 1), (1, 1, 2)(0, 1, 2), (1, 1, 2)(2, 1, 2),$
 $(1, 1, 2)(1, 2, 2), (1, 1, 2)(1, 1, 3), (2, 1, 2)(2, 2, 2), (2, 1, 2)(2, 1, 3), (1, 2, 2)(0, 2, 2),$
 $(1, 2, 2)(1, 0, 2), (1, 2, 2)(1, 2, 3), (0, 0, 3)(1, 0, 3), (0, 0, 3)(2, 0, 3), (0, 0, 3)(0, 2, 3),$
 $(0, 0, 3)(0, 0, 4), (2, 0, 3)(2, 1, 3), (2, 0, 3)(2, 2, 3), (2, 0, 3)(2, 0, 4), (2, 1, 3)(0, 1, 3),$
 $(2, 1, 3)(2, 1, 4), (0, 0, 4)(1, 0, 4), (0, 0, 4)(0, 2, 4), (0, 0, 4)(0, 0, 5), (0, 2, 4)(1, 2, 4),$
 $(0, 2, 4)(0, 1, 4), (0, 2, 4)(0, 2, 5), (1, 2, 4)(2, 2, 4), (1, 2, 4)(1, 1, 4), (1, 2, 4)(1, 2, 5)\};$
 $E(T_3) = \{(2, 0, 0)(0, 0, 0), (2, 0, 0)(2, 2, 0), (2, 0, 0)(2, 0, 1), (0, 2, 0)(1, 2, 0),$
 $(0, 2, 0)(2, 2, 0), (0, 2, 0)(0, 1, 0), (0, 2, 0)(0, 2, 1), (2, 2, 0)(2, 1, 0), (2, 2, 0)(2, 2, 1),$
 $(0, 1, 1)(1, 1, 1), (0, 1, 1)(0, 0, 1), (0, 1, 1)(0, 2, 1), (0, 1, 1)(0, 1, 2), (1, 1, 1)(2, 1, 1),$
 $(1, 1, 1)(1, 0, 1), (1, 1, 1)(1, 1, 2), (0, 2, 1)(1, 2, 1), (2, 0, 2)(1, 0, 2), (2, 0, 2)(2, 1, 2),$
 $(2, 0, 2)(2, 2, 2), (2, 0, 2)(2, 0, 3), (0, 2, 2)(2, 2, 2), (0, 2, 2)(0, 0, 2), (0, 2, 2)(0, 2, 3),$
 $(2, 2, 2)(1, 2, 2), (2, 2, 2)(2, 2, 3), (0, 1, 3)(1, 1, 3), (0, 1, 3)(0, 0, 3), (0, 1, 3)(0, 2, 3),$
 $(0, 1, 3)(0, 1, 4), (1, 1, 3)(2, 1, 3), (1, 1, 3)(1, 0, 3), (1, 1, 3)(1, 1, 4), (0, 2, 3)(1, 2, 3),$
 $(0, 2, 3)(0, 2, 4), (1, 0, 4)(2, 0, 4), (1, 0, 4)(1, 1, 4), (1, 0, 4)(1, 2, 4), (1, 0, 4)(1, 0, 5),$
 $(2, 0, 4)(0, 0, 4), (2, 0, 4)(2, 2, 4), (2, 0, 4)(2, 0, 5), (1, 1, 4)(2, 1, 4), (1, 1, 4)(1, 1, 5)\}.$